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Is CPT Symmetry Conserved in the Neutrino Sector?

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CPT symmetry, the combination of charge conjugation, parity inversion, and time reversal, is a fundamental (and sacred) symmetry of particle and nuclear physics and is conserved in field theories that explain the strong, weak, and electromagnetic interactions. In the lepton sector, CPT symmetry requires that muon neutrino disappearance oscillations be identical to muon antineutrino disappearance oscillations in vacuum. A test of CPT symmetry was recently performed by the MINOS experiment at Fermilab, which, due to its magnetic field, is the first experiment to distinguish μ^- and μ^+ tracks and separately measure the disappearance of muon neutrinos and muon antineutrinos. (Previous experiments have measured a mixture of neutrino and antineutrino oscillations.) Remarkably, MINOS appears to observe a difference between muon neutrino disappearance and muon antineutrino disappearance.

The "atmospheric neutrino problem", a deficit of atmospheric muon neutrinos relative to electron neutrinos, was initially observed by the IMB and Kamioka experiments and was then shown to be due to $\nu_\mu \to \nu_\tau$ oscillations by the SuperKamiokande experiment in 1998. Neutrino oscillations occur if there is mixing between neutrino flavors and if individual neutrino flavors consist of a linear combination of different neutrino mass eigenstates. In the case of two-flavor mixing, e.g. mixing between ν_μ and ν_τ, then the probability that a ν_μ will oscillate into a ν_τ is given by

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E),$$

where θ is the mixing angle, Δm^2 is the difference in squared masses of the two mass eigenstates in eV^2, L is the distance travelled by the neutrino in km, and E is the neutrino energy in GeV.

In addition to the IMB, Kamioka, and SuperKamiokande atmospheric neutrino experiments, the K2K, MINOS, and OPERA accelerator neutrino experiments have confirmed the $\nu_\mu \to \nu_\tau$ oscillation resolution of the "atmospheric neutrino problem". The most precise measurement of $\nu_\mu \to \nu_\tau$ oscillations comes from the MINOS experiment, which consists of two similar detectors [1] located at distances of 1.04 km (Near Detector, ND) and 735 km (Far Detector, FD) from the particle production target. Neutrinos are produced by 120-GeV protons from the Fermilab Main Injector interacting on a graphite target, followed by magnetic horns that focus either positive pions and kaons to produce a dominantly ν_μ beam or negative pions and kaons to produce an enhanced $\bar{\nu}_\mu$ beam. The ND, located at Fermilab, and the FD, located in the SOUDAN Underground Laboratory in northern

Minnesota, (see Fig. 1) are tracking calorimeters consisting of planes of magnetized steel (~ 1.4T) interspersed with planes of plastic scintillator. Neutrino interactions in the steel produce muons whose energy is measured by either the range of the contained muon track or by the curvature of the muon track in the magnetic field. This curvature also determines the charge of the muon and whether the incident neutrino is a ν_μ or $\bar{\nu}_\mu$. The hadronic energy is determined from the total amount of light produced in the scintillator. The total neutrino energy is the sum of the muon energy and the associated hadronic energy. MINOS is designed to make a precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance by comparing the neutrino energy distribution in the FD (after neutrinos have oscillated) to the neutrino energy distribution in ND (before neutrinos have oscillated).

MINOS has made the world's best measurement of ν_μ disappearance oscillations [2]. Using a data sample corresponding to 7.25×10^{20} protons on target (POT), MINOS measures the best-fit ν_μ oscillation parameters to be $\Delta m^2 = 2.32 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1.0$. Antineutrino experiments are difficult, due to their low event rate compared to neutrino experiments. Nevertheless, based on 1.71×10^{20} POT, MINOS has also reported the first direct observation of $\bar{\nu}_\mu$ disappearance oscillations [3] and measures the $\bar{\nu}_\mu$ oscillation parameters to be $\Delta m^2 = (3.36^{+0.46}_{-0.40}(stat.) \pm 0.06(syst.)) \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 0.86^{+0.11}_{-0.12}(stat.) \pm 0.01(syst.)$. The no-oscillation hypothesis in antineutrino mode is disfavored at 6.3 standard deviations; however, it is significant that the ν_μ and $\bar{\nu}_\mu$ disappearance parameters appear to be different. As stated in the paper, "The probability that the underlying ν_μ and $\bar{\nu}_\mu$ parameters are identical is 2.0%."

What could explain this possible difference between muon neutrino and muon antineutrino disappearance? First, it is possible that the difference is just due to a statistical fluctuation. This possibility will be tested by additional MINOS data to be taken over the next few years. If the difference is not a statistical fluctuation, then it is possible that it is due to nuclear effects [4], which can cause a difference in the energy reconstruction of neutrino events compared to antineutrino events. Such a difference could arise if the hadronic energy is mis-reconstructed, as neutrino events have a higher fraction of hadronic energy than antineutrino events. As the neutrino energy is needed for the determination of Δm^2, a mis-measurement of the neutrino energy then results in an incorrect measurement of Δm^2.

If the apparent difference between muon neutrino and muon antineutrino disappearance is not due to a statistical fluctuation or to nuclear effects, then we would have to consider

new physics beyond the Standard Model. Indeed, global fits to the world neutrino and antineutrino oscillation data [5] encounter tension between the neutrino and antineutrino data sets and favor different neutrino and antineutrino oscillation parameters. One possible beyond the Standard Model solution involves non-standard interactions [6], which would affect neutrinos and antineutrinos passing through matter (as is the case for MINOS) differently. A more extreme possibility is that Lorentz symmetry is violated [7] or CPT symmetry is violated [8], and that neutrino masses and mixing angles are different from antineutrinos. If this were the case, then the impact on nuclear and particle physics would be profound.

Fortunately, there are several experiments that are either taking data or being constructed that will be able to test this possible difference between muon neutrino and muon antineutrino disappearance. The SciBooNE and MiniBooNE experiments at Fermilab, located at distances of 0.10 km and 0.54 km from the neutrino source, took data at the same time in both neutrino mode and antineutrino mode and are performing a joint analysis of their disappearance data. Also, the T2K experiment in Japan has detectors at distances of 0.28 km and 295 km, and is now taking data with neutrinos. T2K has the capability of switching to antineutrinos in a few years. In addition, the NOνA experiment at Fermilab is under construction and should begin taking data in a couple of years with detectors at distances of 1.0 km and 810 km. Finally, the IceCube experiment at the South Pole is measuring high-energy atmospheric neutrinos and antineutrinos and will be sensitive to disappearance over distances of approximately 100 to 10,000 km. Will neutrino experiments continue to surprise us? Is CPT symmetry conserved in the lepton sector? Stay tuned.

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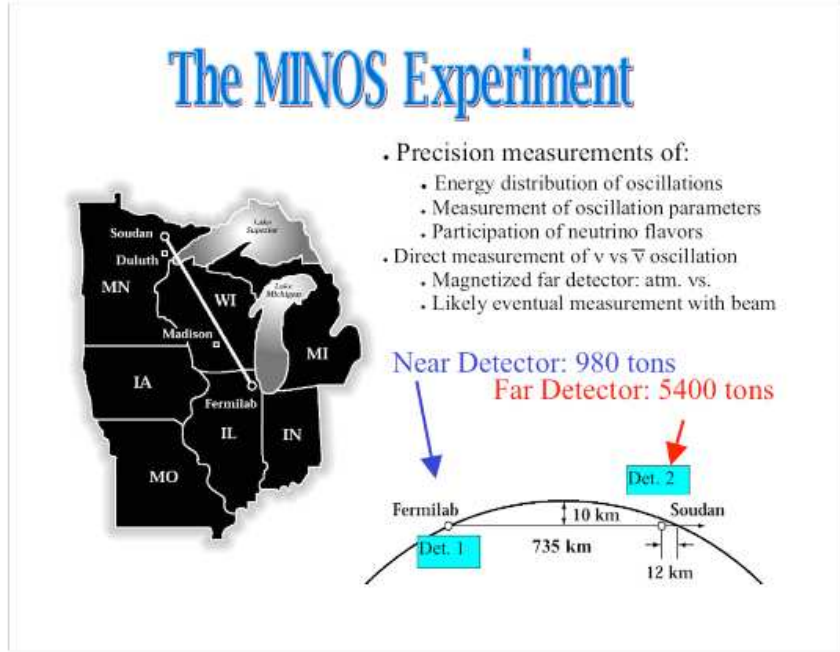
FIG. 1: *The MINOS experiment consists of two similar detectors located at distances of 1.04 km (Near Detector, ND) and 735 km (Far Detector, FD) from the neutrino production target. The ND is located at Fermilab, and the FD is located in the SOUDAN Underground Laboratory in northern Minnesota.*

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